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Electrification of excavators

Electrical configurations, carbon footprint and cost assessment of retrofit solutions

By Marianne Kjendseth Wiik, Kristin Fjellheim, Jon Are Suul, Kamal Azrague

Technology for electrification of transport is currently undergoing a rapid development which is necessary for reducing greenhouse gas (GHG) emissions. On a global level, the transport sector is responsible for around 12% of the world's GHG emissions. While the introduction of battery-electric cars is leading the way in terms of commercial scale, developments are also progressing towards electrification of heavy-duty vehicles for road freight transport and for coastal transport by battery-electric ships. The performance of modern Li-ion batteries is also enabling electrification of other types of machines or small vehicles that have traditionally been powered by internal combustion engines (ICEs). However, until recently, the developments towards electrification have been mainly directed towards applications with either a large market for series-produced vehicles, like electric cars, or a high degree of individual engineering for each unit, like battery-electric ships. Still, there are several application areas where other types of vehicles and machines contribute significantly to GHG emissions.

In many urban environments, the construction sector is a significant contributor to GHG emissions. In Oslo municipality in Norway, around 60 - 100,000 tCO_{2e} arise from the construction industry. Over 90% of these GHG emissions arise from activities related to road transport to and from construction sites as well as from the operation of construction machinery on site. As a response, Oslo municipality has set ambitious targets for cutting GHG emissions from construction site activities by 95% by 2030. These targets are currently being applied as a basis for public procurement processes intended to drive a development towards zero emission construction sites.

For the construction of buildings, the groundwork and preparation of the site is the construction phase that is traditionally the main contributor to high GHG emissions. This is mainly due to emissions from construction machinery powered by diesel engines. Among the construction machinery, recent studies on Norwegian construction sites indicate that excavators are responsible for more than 50 % of these emissions. Thus, the construction industry in Norway, in collaboration with Oslo municipality, has been responding to the challenge of reducing GHG emissions by electrifying construction machineries with a special focus on excavators. Since the first pilot projects on fully electrifying excavators were started in Norway around 2018, the Norwegian Association for Machinery Wholesalers (MGF) have reported that over one hundred large electric excavators (over 8t) have been introduced in Norway by the end of 2021. Furthermore, around 250 electric excavators have entered the Norwegian market during 2022

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which corresponds to a 15% market share of all new excavators. This is an important achievement when considering that 40% of all medium and large construction machines in Norway are excavators.

This article discusses the electrification of excavators by retrofit installation of electrical drivetrains for replacing the original diesel engine. Such conversion from conventional fossil fuels to electrified operation serves to demonstrate the feasibility of reducing greenhouse gas (GHG) emissions from construction machineries. Small-scale production series based on retrofit installation also enable demonstration and gradual introduction of zero emission technology, while providing the first steps towards establishing a market that can allow for future series production of fully electrified excavators. The electrical configurations selected for retrofitting of crawler excavators in three different weight classes (8.5t, 17.5t and 38t) are discussed. Analysis of carbon footprint and costs are presented as a basis for guiding further development and future large scale market introduction of electric excavators for reducing the emissions from the construction industry.

Trends towards electrification of the construction sector

Internationally, there has been increasing attention towards the development of technology for reducing GHG emissions from construction equipment during the last decade. A large part of the resulting efforts in terms of scientific publications and development of industrial products have been dedicated towards hybrid solutions for recovering regenerated energy and for improving fuel efficiency by optimising the operation of Internal Combustion Engines (ICEs) as the only energy source. However, solutions for fully electrified power supply, either directly from the grid during operation or by battery-based operation, are also receiving increased international attention for ensuring zero emission operation.

In the European construction machinery market, prototypes for mini, small, and middle-sized electric excavators are already becoming available. Similar developments are also expected for wheel loaders and other more specialized vehicles or machines that have traditionally been powered by ICEs. The Committee for European Construction Equipment (CECE) have published a position paper on the role of construction equipment in decarbonising Europe and have created a map of an expected path to market phases as shown in Figure 1. The path shows three phases for market penetration, whereby the first phase involves prototype pilot projects followed by productionisation and lastly series production. As will be discussed in the following, Norway has recently transitioned from phase one to phase two for electrification of excavators.

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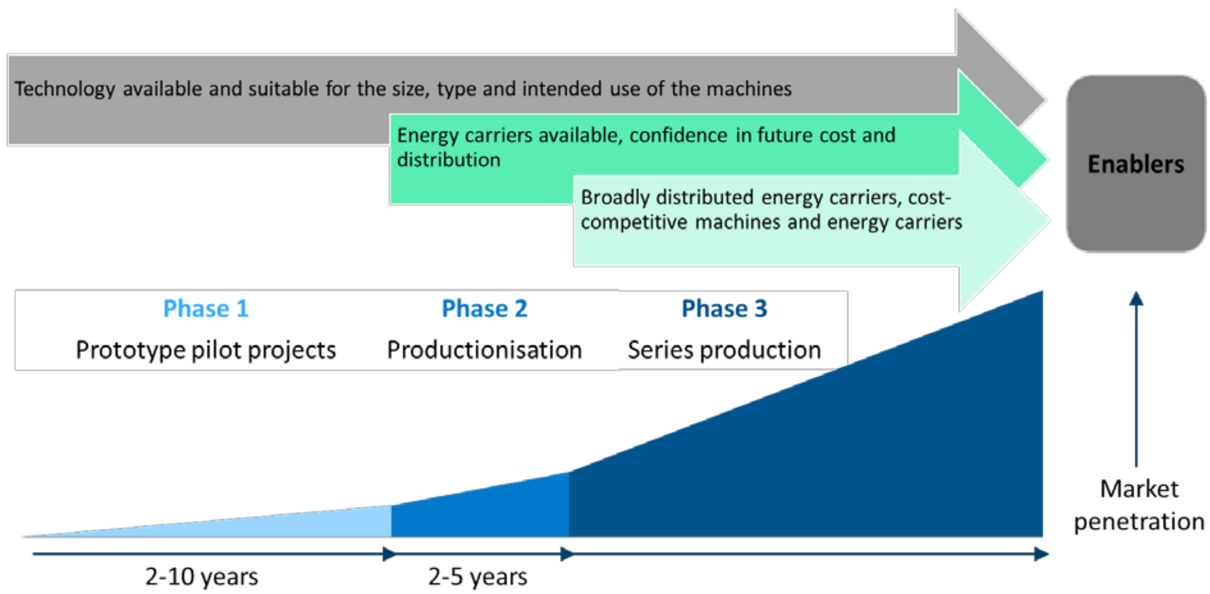

Figure 1 CECEs path to market phases. Figure based on data from CECE. The role of construction equipment in decarbonising Europe. CECE; 2021 Apr. Report No.: Position paper

To reach this point, several studies have been carried out in Norway over the last few years to investigate the required technical advancements for the electrification of larger excavators and to test electric excavator prototypes on construction sites to compile knowledge and practical experiences. An impact assessment of emission free construction processes in Oslo municipality has found that the demand for electric construction machineries is currently higher than production capacity. Manufacturers resolve technological challenges in different ways, for example one manufacturer is committed to converting their production lines to electric powertrains, whilst another manufacturer is converting off-the-shelf diesel machinery to electric operations. For some cases, replaceable battery solutions are considered, while other applications are based on direct electrification by dynamic cables. Nearly all manufacturers have already started providing small-scale construction machineries (under 8t), whilst others have begun to electrify small (8-16t), medium (16-23t) and large (over 23t) machines. New actors are also emerging on the construction market in Norway to offer various mobile, temporary battery container solutions, energy tracking tools and power demand calculators. In addition, the Norwegian standardization body is working on a new technical standard (SN/TS 3770) which will give guidance for emission free building and construction sites.

In the period since 2018, several prototypes for battery-electric excavators and excavators with direct cable-based electric power supply during operation have been developed for the Norwegian market by retrofitting conventional diesel excavators from mainly two different suppliers. During the same period, examples of electrified machinery for zero emission operation of a quarry has also been demonstrated by Volvo CE in Sweden. When starting the development of the retrofit solutions in 2018, the feasibility of alternative powertrain technologies was assessed for excavators of various size classes available in the Norwegian market and expectations for introduction of prototypes were predicated. This assessment

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formed the basis for the development of the retrofit solutions provided in Norway by an official retailer of construction equipment from Japan. This assessment has since been updated to the market phases (unsuited, possible, prototype, production, and series production) defined by CECE, see Table 1. The following discussions refer specifically to three constructed retrofit prototypes of electrified crawler excavators as marked by bold text in Table 1. These prototypes belong to three classes of machines, namely 8.5t (small), 17.5t (medium), and 38t (large) excavators.

*Table 1 Overview of the powertrain technologies for excavators of different size classes in the Norwegian market. * The electric excavators studied in this paper fall into these categories.*

<table>
<tr><th>Powertrain</th><th>Useful energy</th><th>Range</th><th>Mini 30kW</th><th>Small 30-60kW</th><th>Medium 60-100kw</th><th>Large 100-200kW</th><th>XL 200-400kW</th><th>Gigantic 400kW+</th></tr>
<tr><td>Diesel</td><td>30%</td><td>Two shifts</td><td colspan="6">Series production</td></tr>
<tr><td>Cable electric</td><td>95%</td><td>Cable length</td><td colspan="3">Possible</td><td colspan="3">Production*</td></tr>
<tr><td>Battery cable electric</td><td>92%</td><td>Cable length & battery</td><td>Possible</td><td colspan="4">Production*</td><td>Possible</td></tr>
<tr><td>Battery electric</td><td>85%</td><td>5 – 7 hours</td><td colspan="5">Production</td><td>Possible</td></tr>
<tr><td>Battery fuel cell</td><td>50%</td><td>One shift</td><td colspan="2">Unsuited</td><td>Possible</td><td>Prototype</td><td colspan="2">Possible</td></tr>
</table>

Technical specification of the evaluated excavators

The largest excavator under study, the 38t unit, was developed for operating with a direct electrical power supply via a dynamic cable. An overview of the electrical system layout, indicating the main components introduced in the onboard powertrain and for the power supply via dynamic cables is shown in Figure 2a. The onboard system consists of an active rectifier supplying a local dc-bus where the

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main load is an inverter driving the electrical motor that is used to replace the originally installed diesel engine. The system is rated for a maximum power of 197 kW. The excavator is operated from a regular 400 V AC grid which supplies a mobile substation with a transformer for galvanic separation, a circuit breaker for protection and any necessary instrumentation for measurements and power metering. Another mobile container solution with remote controlled cable drums is used to manage the dynamic cables for connecting to the excavator, and this container can be moved around on the construction site by the excavator to ensure sufficient operating range. A photograph of the excavator and the container for the cable drums during operation at a construction site is shown in Figure 3.

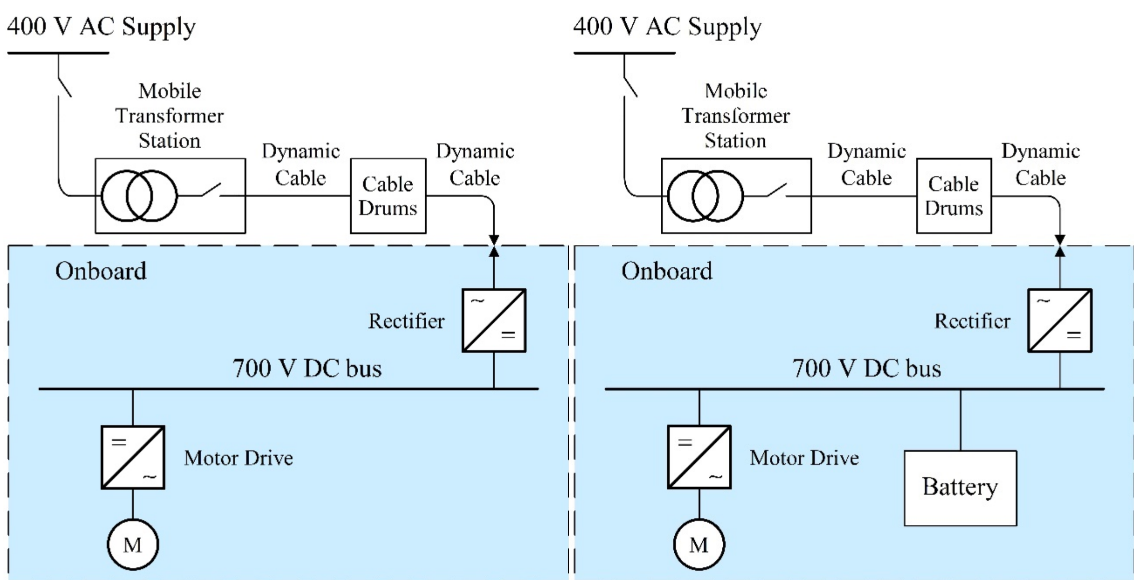

Figure 2a (left) Electrical system configuration of the 38t cable electric excavator

Figure 2b (right) Electrical system configuration of 8.5t and 17.5t battery electric excavators

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Figure 3 Photograph of the 38t excavator and cable container on-site at Biri care home in Gjøvik, Norway. Source: NASTA, used with permission

The 17.5t excavator was designed with the same electrical system configuration as the 38t prototype but extended with a small onboard battery as shown in Figure 2b. The battery is designed for peak-shaving to limit the load on the local power system. Furthermore, the battery allows for operation without power supply for a limited time, for instance for operations outside the range of the supply cable or for transport between construction sites. Beyond the battery, the system components are functionally identical to what has been explained for the 38t prototype, but with a correspondingly lower power rating. A photograph of the prototype during operation for refurbishing Olav Vs Street in Oslo is shown in Figure 4.

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Figure 4 Photograph of the 17.5t excavator on-site at Olav Vs Street in Oslo, Norway. Source: SINTEF

The 8.5t excavator also has the same electrical configuration as the 17.5t prototype, but with a battery designed for regular operation of the machine. Thus, this machine is intended to operate without the dynamic cable arrangement explained for the 38t and 17.5t machines and with regular quick charging during breaks. A photograph of the prototype during charging at the same construction site as the 17.5t machine is shown in Figure 5.

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Figure 5 Photograph of the 8.5t excavator charging on-site at Olav Vs Street, Oslo, Norway. Source: SINTEF

A summary of key parameters for the three electric excavators is provided in Table 2. All three excavator prototypes are designed to have operating performances equivalent to corresponding conventional, diesel units and have been tested under real conditions as shown by the photos above. Thus, after the initial testing, these machines have been made commercially available and further information on the machines can be found in the manufacturer's product specifications.

Table 2 Summary of key parameters of the studied excavators

Machine size	38 t	17.5 t	8.5 t
Power supply in operation	Cable	Cable and battery	Battery
Rated power	197 kW	86 kW	42 kW
Battery capacity	-	42 kW	100 kW

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Analysis of the carbon footprint

Lately, several studies have compared fossil fuel powered vehicles with their electrified versions with respect to GHG emissions using life cycle assessment (LCA) methodology. In most cases, only the operation phase is considered, resulting in a comparison of the impact of the energies used (fossil fuels or electricity). The complexity of the design of the vehicles, and the differences in the production processes and geographic contexts, indicate that a complete life cycle comparison should be performed from the extraction of raw materials to the end-of-life phase, including any necessary infrastructures and potential reuse or recycling after end of life. Besides the carbon footprint, economic assessments, and comparisons of electric versus fossil fuel vehicles have also been largely investigated using either life cycle cost (LCC) or cost benefit analysis. To our knowledge, no study has yet covered the comparison of diesel excavators with their electrified versions in terms of carbon footprint and life cycle costs.

The goal of the carbon footprint assessment presented is to ascertain the emission reduction potential of converting diesel excavators to the studied electrified equivalents. Life cycle inventory data has been collected from the manufacturers and the Ecoinvent v3.1 database. The life cycle inventory models are developed in SimaPro Analyst v9.0.0.48, and the impact assessment is carried out according to IPCC 2013 GWP 100a method. A sensitivity analysis on electricity emission factors has also been carried out using the Norwegian (0.018 $kgCO_{2e}$/kWh) and European (0.136 $kgCO_{2e}$/kWh) electricity mixes according to the operational energy use scenarios provided in the Norwegian Standard NS 3720: 2018 "A method for GHG calculations for buildings." The functional unit is one-hour operation given 1800 hours of operation per year. The reference period and service lifetime of the diesel and electric excavators is set to 10 years. The same material inventory is used for both a diesel and electric excavator. However, the diesel power train components are then replaced with the components necessary for an electric excavator. An overview of the system boundary is shown in Figure 6.

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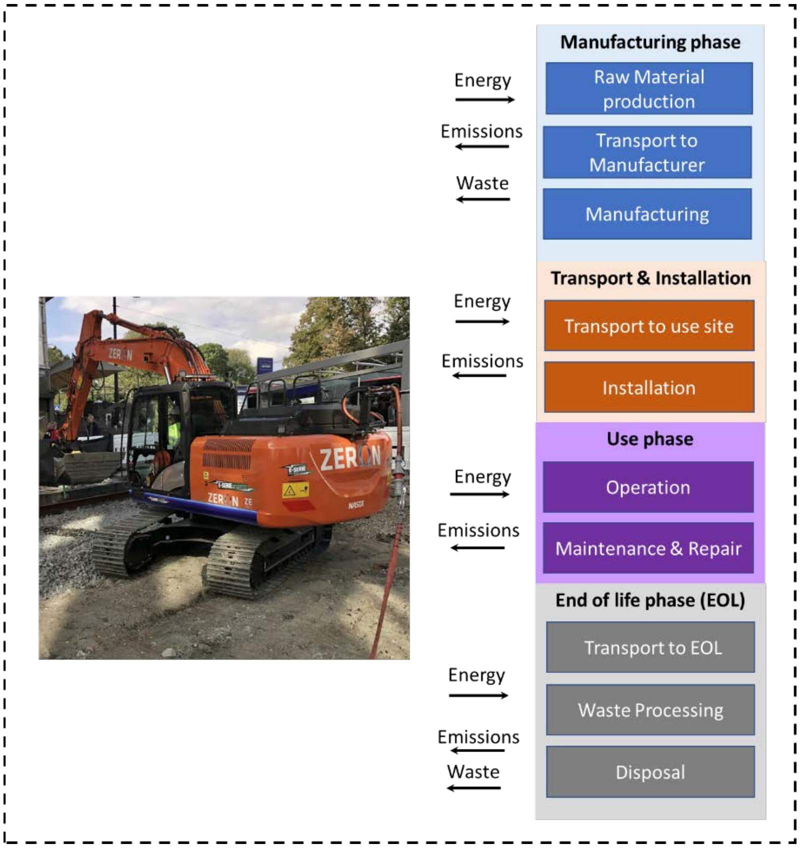

Figure 6 System boundary for the comparative carbon footprint analysis of diesel and electric excavators

Manufacturing

All three excavators are manufactured in Japan and transported to Larvik in Norway by container ship. The 15t 'hydraulic digger' process from Ecoinvent is used as a starting point and modified to 8.5t, 17.5t and 38t diesel excavators. These processes are then modified further to electric excavators using background information from the manufacturer. The European electricity mix unit processes (RER) are replaced with Japanese unit processes that use the Japanese electricity mix (JP). When this was not available, rest of world (ROW) unit processes were used. On arrival in Larvik, the excavators underwent a rebuilding process, these rebuilding processes use Norwegian unit processes that use the Norwegian electricity mix (NO). Each excavator required different components depending on the technology being integrated such as batteries (8.5t and 17.5t), electrical engines (all excavators), powertrains (all excavators), inverters (all excavators), 230 m cable (17.5t and 38t excavator), transformer for galvanic isolation (17.5t and 38t excavator), and storage container (17.5t and 38t excavator).

Transport and Installation

For the analysis, it is assumed that the diesel-powered and electric excavators are further transported from Larvik to Oslo (128 km) and connected on-site. This installation process requires charging infrastructure such as a charging cable, storage container and cable drum. All excavators operate for one

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year on the construction site before they are moved to a new construction site within the Oslo area. The distance between one construction site to the next is negligible.

Use

Table 3 provides an overview of the operational energy use of each excavator. All excavators have 1800 hours of operation per year. The emission factor for diesel is taken from Ecoinvent and is 3.32 kg CO_2e/litre. According to NS 3720:2018 two GHG emission factors are supplied for electricity. The first is based on a European energy mix factor of 0.136 kg CO_2e/kWh which accounts for the exchange of electricity with the rest of Europe, and the second is based on the Norwegian (NO) energy mix factor of 0.018 kg CO_2e/kWh which is mainly based on hydropower.

Table 3 Energy use per excavator

	Unit	8.5 t	17.5 t	38 t
Diesel	l/h	5.5	10	30
Electric	kWh/h	13	28	100

End of life

When the diesel excavators reach their end of life, it is assumed that they will be dismantled and recycled. When the electric excavators reach their end of life, the batteries and cables are sent to disposal, the containers are sold at the second-hand market, the electrical engine and powertrain are dismantled and recycled, and the aluminium in the inverters is recycled. It is acknowledged that the lifetime of the excavators may be longer than the 10-year reference study period used in this study. In Norway, it is common practice for construction machinery to be sold to the second-hand market after the machine has accrued 10,000 hours of operation (around 6 years). However, for the purposes of this carbon footprint assessment the reference study period has been set to 10 years to reflect that the machines have a longer service lifetime than their first market use. It is also acknowledged that the service life of electric excavators is still an unknown factor since the electric excavators produced so far are either prototypes or small-scale production series since 2018. Therefore, the reference study period for the electric excavators has been set to the same as for the diesel excavators until better data on the lifetime of electric excavators is made available.

Carbon footprint results

The carbon footprint results (Figure 7 and 8) show the total emissions for the 8.5t, 17.5t and 38t diesel and electrical excavators with both EU and NO electricity factors. Figure 7 shows a significant reduction in GHG emissions by converting all types of diesel excavators to electrical excavators; regardless of whether the EU or NO electricity factor is used. The results in Figure 8 show that most of the GHG emissions from the diesel excavators are from operation energy use (96-97 %) followed by production (3-4 %). For the electrical excavators using the EU electricity factor, operational energy use also stands for the highest emissions (45 % for 8.5t, 49 % for 17.5t and 64 % for 38t) followed by production (38 % for 8.5, 39 % for 17.5t and 31 % for 38t). When using the NO electricity factor, the highest contribution to GHG emissions for the electric excavators is from production (62 % for 8.5t, 69 % for 17.5t and 71 % for 38t) followed by operational energy use for 17.5t (11 %) and 38t (19 %) and by the production stage for 8.5t excavator (22%). Regardless of the size of the excavator, these results indicate that the share of GHG emissions from operation increases with the amount of fossil fuel inputs either directly as fuel or indirectly in the production of electricity.

In terms of GHG emissions, the contribution from manufacturing the excavator presents only minor differences between the diesel and electric alternatives (Figure 7). This indicates that the replacement of diesel engines with an electric motor, electronics and battery do not significantly impact on the GHG emissions occurring during the raw material extraction and supply or during the manufacturing of the excavators. On the other hand, the electrification of excavators allows a significant reduction in GHG emissions associated with the operation phase especially if the electricity mix includes a large proportion of renewable electricity. Compared to their diesel counterparts, electric excavators would allow, over a 10-year period, a cut in GHGs emissions of 3111 tCO_{2e} for the 38t, 1309 tCO_{2e} for the 17.5t and 675 tCO_{2e} for the 8.5t excavator if the European electricity mix is used or 3702 tCO_{2e} for the 38t, 1474 tCO_{2e} for the 17.5t and 751 tCO_{2e} for the 8.5t excavator if the Norwegian electricity mix is used. These results correspond to a reduction of90 – 96% in GHG emissions with the conversion from diesel to electric excavators, depending on which electricity mix is used. This finding is in accordance with those reported in the literature for the electrification of transports vehicles such as trucks, buses, and cars. The contribution of installation on the construction site is site specific as it is associated with the transport of the excavator to the construction site which is achieved by diesel truck. However, it can be argued that a prestigious emission free construction project should not be transporting electric excavators with diesel transport to and from the construction site and would thus have lower GHG emissions from transport to site by using electrified transport. Thus, the major contributions of the electric excavators are mostly from raw material supplies and manufacturing while for the diesel counterparts it is emissions from operation.

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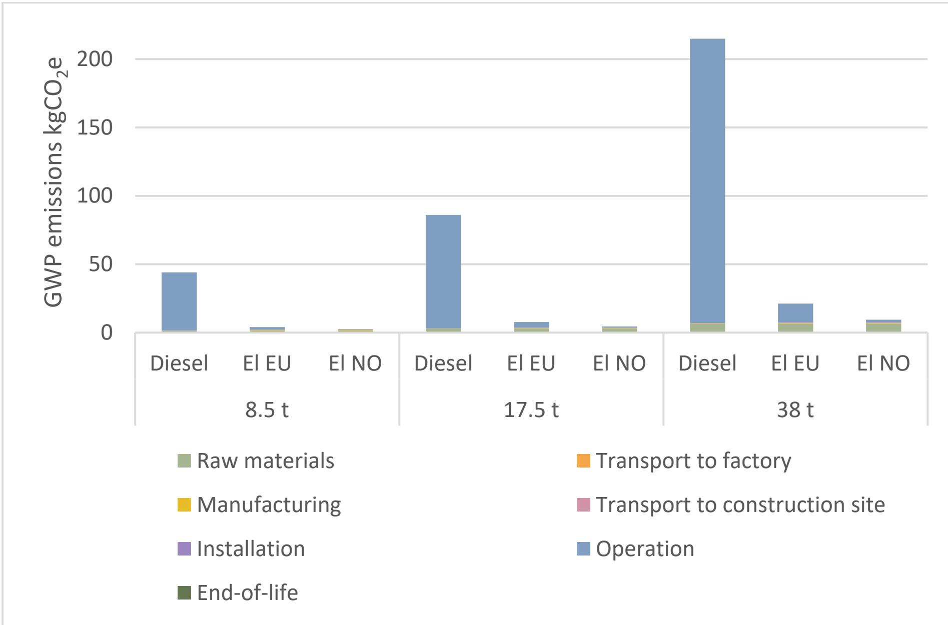

Figure 7 Total GHG emissions per functional unit (1 hour operation) for all excavators.

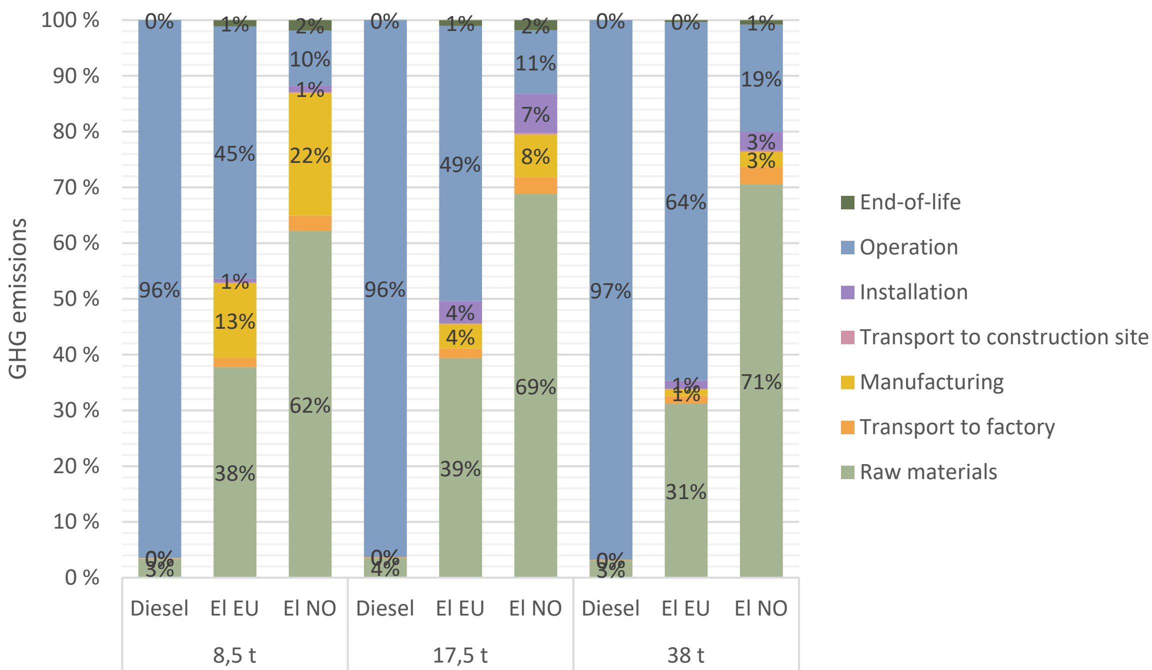

Figure 8 GHG emissions for all excavators per life cycle stage

Cost assessment

Life cycle costing (LCC) is the method used to calculate the sum of all costs associated with the excavators over their whole lifetime and to compare the cost between different alternatives. The LCC calculation is based on the net present value (NPV) of all cost elements and provides the present value

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of all future costs depended on the discount rate and inflation rate. The functional unit is similar to the functional unit used in the carbon footprint, namely Norwegian kroner (NOK) (1NOK = 0.0998 EUR) per hour of excavator operation given a reference study period of 6 years and 1800 operational hours per year. For the cost analysis the reference period of 6 years is used as this is the standard operating life span in the market. The excavators have a longer lifespan, but after 6 years they are often either sold on the second hand marked or undergo significant maintenance. The discount rate is set at 5 % and the inflation rate at 2.2 %. All prices are in Norwegian kroner.

The goal of the LCC is to ascertain the economic feasibility of the 8.5t, 17.5t, and 38t electric excavators compared to the diesel excavators of equivalent size. The LCC has been carried out according to ISO 15686-5: 2017 "Building and construction assets - service life planning. Part 5: Life-cycle costing." Life cycle cost data is gathered from the manufacturer and contractor. Total costs include purchase costs (including installation costs), operating costs, maintenance costs, other costs (including insurance costs) and remnant value.

Purchase cost

The purchase costs for the 8.5t, 17.5t and 38t diesel and electric excavators are listed in Table 4. In addition to the purchase cost, there is an installation cost for the 17.5t and 38t electric excavators of 650 000 NOK for the electric connection, the cable, container, and galvanic isolation. This does not occur for the 8.5t excavator as it only runs on batteries, and it is assumed that the original charging connection is included in the purchase cost.

Operation cost

Energy consumption is the main cost of operation for both diesel and electric excavators. The energy consumption for each excavator is listed in Table 3. The price of diesel and electricity is based on the price range in the Norwegian report Klimakur 2030 for the year 2022. Diesel prices consists of the cost per litre excluding fees but including a CO_2 tax per litre. For electricity the price includes the electricity cost per kWh and the electricity fee. As the energy prices are fluctuating both the estimated prices and actual prices for 2022 are used in the analysis (collected from SSB and Circle K). Prices are listed in Table 4.

Maintenance cost

The maintenance costs include yearly service costs per hour of operation, and it is assumed that all the machines have an operating time of 1800 hours per year. Table 4 shows the service cost per hour and the service cost per year given 1800 hours of operation for each excavator. The maintenance cost for electric and diesel excavators is assumed to be the same as many of the tasks are routine tasks that must be performed on the machines regardless of type of energy carrier. This is a conservative assumption since electric excavators should require less maintenance for the motor, whilst all maintenance for the hydraulic and mechanical parts will be the same.

Other cost

Other costs include yearly insurance of 2.5 % of the purchase cost for all excavators.

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Residual value

The residual value is based on an estimate of where the second-hand market for excavators will be in 6 years. Based on the market today it is assumed that its minimum value should be about 25 % of the purchase cost for both diesel and electrical excavators.

Table 4 Purchase, installation, operation, and maintenance costs per excavator.

	Unit	8.5 t diesel	8.5 t electric	17.5 t diesel	17.5 t electric	38 t diesel	38 t electric
Purchase cost	NOK/unit	1 300 000	4 000 000	1 650 000	4 000 000	2 100 000	4 370 000
Installation cost	NOK	0	0	0	650 000	0	650 000
Operation cost (estimated 2022)	NOK/l	8.91	0	8.91	0	8.91	0
	NOK/kWh	0	0.90	0	0.90	0	0.90
Operation cost (actual prices 2022)	NOK/l	16.38	0	16.38	0	16.38	0
	NOK/kWh	0	1.89	0	1.89	0	1.89
Maintenance cost	NOK/h	26	26	33	33	33	33
Other cost	NOK/year	32 500	100 000	41 250	116 250	52 500	125 500
Residual value	NOK/unit	325 000	1 000 000	412 500	1 162 500	525 000	1 255 000

Cost assessment results

Figure 9 shows the accumulated cost for each excavator calculated over a 6-year planning horizon with both estimated energy prices for 2022 and actual energy prices for 2022. Figure 9 shows that the 38t will become more economically favourable than the diesel excavator equivalent with today's energy prices, as shown by the intersection of accumulated costs occurring in year 5. On the other hand, the electric 8.5t and 17,5t excavator displays higher accumulated costs than its diesel version over the 6-year planning horizon both with estimated and actual energy prices. This is mainly due to the initial cost of the batteries.

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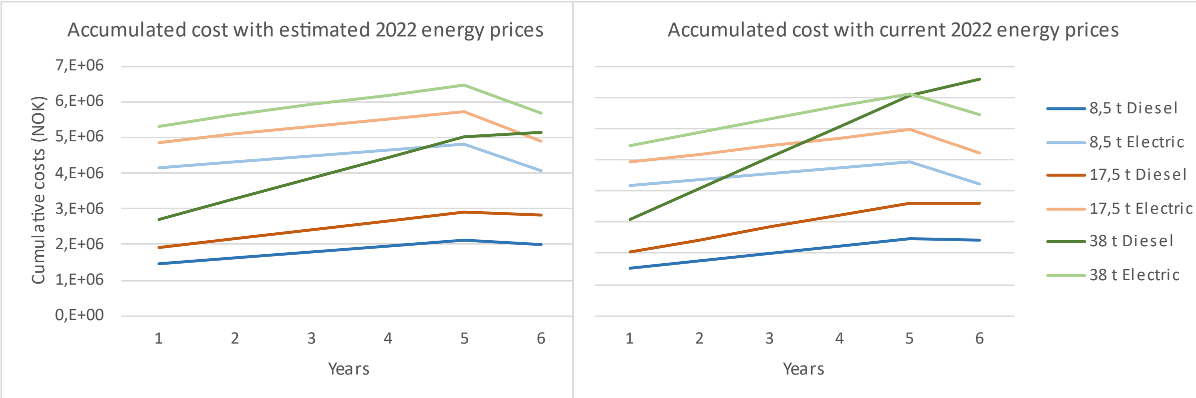

Figure 9 Accumulated costs (NOK) showing the 6-year planning horizon

Figure 10 shows the sum of costs per life cycle category after the end of the 6-year planning horizon for estimated energy cost and actual energy cost in 2022. The results show that the main cost for all electrical excavators are acquisition costs followed by operation and other costs for the 8.5t and 17.5t excavators and operation costs for the 38t excavator. For the diesel excavators the main cost for the 8.5t and 17.5t excavators is the acquisition cost followed by operation costs, maintenance costs and other costs while for the 38t excavator the largest cost is the operation cost followed by acquisition, maintenance, and other costs. The higher operating costs due to higher energy prices compared to estimated energy prices is the reason the 38t electric excavator has a lower life cycle cost than the diesel excavator.

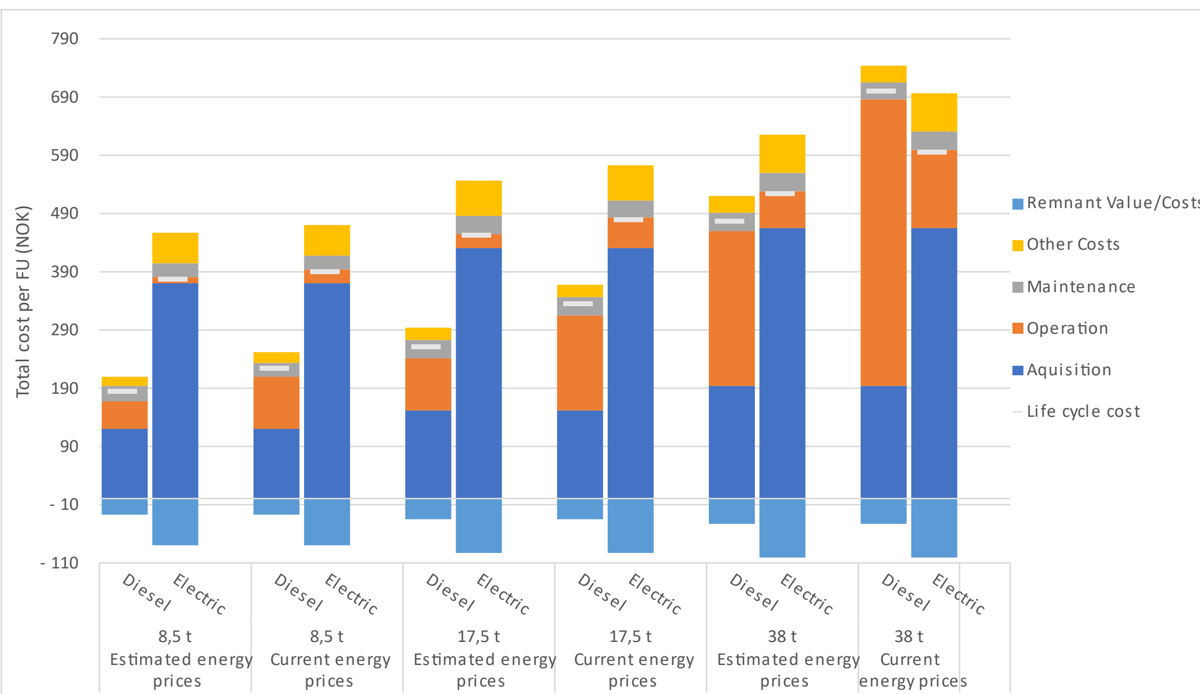

Figure 10 Sum of costs (NOK) per life cycle category per FU (operating hour) after 6-year planning period

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Table 5 shows the NPV of the different excavators over the planning horizon of 6 years and the annual cost when looking at the period of 6 years with estimated and actual energy prices. The table also shows the increase in total cost due to increased energy prices showing that the operating costs for diesel excavators will be more affected by fluctuating energy prices.

Table 5 Net present value (NVP) of all excavators after 6-year planning horizon and annual cost

		Unit	8.5 t diesel	8.5 t electric	17.5 t diesel	17.5 t electric	38 t diesel	38 t electric
Estimated energy prices 2022	Total costs (after 6 years)	NOK	1 990 772	4 078 018	2 817 221	4 893 700	5 156 857	5 661 762
	Annual cost	NOK/year	331 787	679 670	469 537	815 617	859 476	943 627
Actual energy prices 2022	Total costs (after 6 years)	NOK	2 434 440	4 217 000	3 623 981	5 193 046	7 577 137	6 431 508
	Annual cost	NOK/year	405 740	702 833	603 997	865 508	1 262 856	1 071 918
Change in total cost		%	22	3	29	6	47	14

Outlook

This paper has presented the technical basis as well as the environmental and economic performance results for the electrification of 8.5, 17.5 and 38t electric excavators in Norway compared to their diesel equivalents. The carbon footprint results show that the operational phase is the main contributor to GHG emissions for a diesel excavator, whilst switching to an electric engine using either the Norwegian or European electricity mix leads to much lower total GHG emissions. The cost assessment shows that electric excavators have a higher investment cost than their diesel equivalent. However, when evaluating probable market developments, electric excavators can become more cost efficient over their lifespan.

This paper has investigated the electrification of diesel excavators in Norway with different retrofit solutions. The results from the presented study can be used to further progress the electrification of construction machinery in Norway to full-scale series production. The results may be applied to other types of construction machinery and may also be applied to other markets in Europe and internationally. The retrofit electrification of excavators may also be applied to existing diesel excavators and other types of construction machinery.

For Further Reading

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Adapted from Luis(Nando) Ochoa,

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